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AN OVERVIEW ON THE DESIGN OF FINAL COVERS FOR LANDFILLS

Report No. 90-177-K

H. T. Chan
Senior Engineer
Soil Sciences Section
Civil Research Department

Abstract

As an initial part of a comprehensive study on the design and construction of covers on solid waste landfills or mounds, a general review of literature information on cover design and other relevant topics has been undertaken. The report summarizes the pertinent findings.

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To Mr. C. W. Dawson
Head, Fossil Projects Planning
Generation Planning &
Approvals Program Department
Design & Dev. Division - Gen

Attn: Mr. D. K. Fung

AN OVERVIEW ON THE DESIGN OF FINAL COVERS FOR LANDFILLS

1.0 INTRODUCTION

The cover on a waste disposal site or a landfill site is a man-made hydraulic barrier that seals off the site (or landfill) after the filling is complete. It usually consists of multi-layers of earthwork accompanied by a well designed surface or subsurface drainage system. Owing to its complexity, it is also referred to as a cover system. The main purposes of a cover system are reducing the amount of leachate generation in the waste, preventing human or animals from contacting the wastes and, in some cases, acting as a dust control barrier and preventing the release of hazardous gas to the environment. Since a waste disposal or landfill site usually occupies a large area of land, the cost of providing a good cover system is also proportionally high. It is therefore important that a rational approach must be employed in order to come up with a cost-effective design.

2.0 COVER SYSTEM

A cover system is a properly contoured, relatively impermeable cap which is composed of a multi-layer of earthwork with each layer playing a different role. Presented in Figure 1 is a typical structure of a cover system. The most important layer is the hydraulic barrier whose fundamental function is to minimize the surface infiltration from entering the waste. The

other layers mainly serve either to reduce further infiltration or to protect the hydraulic layer. In a situation where gas generation is anticipated, a gas control layer can also be included.

The upper-most layer of a cover system must be able to resist erosion caused by surface runoff and blowing wind, to resist cracking and freeze-thaw deterioration and to provide protection for the layers below. A vegetative soil layer is usually recommended if long-term stability and aesthetic appearance are taken into consideration. A vegetative layer also promotes evapotranspiration, thereby further reducing infiltration. If short-term stability is considered, mulching and chemical stabilization can be used to provide protection against excessive soil erosion for a period of less than one year.

The second layer is a filter layer which is underlain by an internal drainage layer. Some of the infiltration through the upper-most layer will be drained away in the drainage layer. It is noted that a filter layer is required to prevent piping whenever materials of strongly contrasting gradation are placed adjacent to one another with the presence of ground water seepage. The drainage layer is optional in a cover system.

The next layer is the biotic barrier. Its main purpose is to prevent the intrusion of plant roots and burrowing animals. At present, the most feasible method of controlling penetration of plant roots lies in the careful selection of short-rooted grasses. Research aimed at preventing burrowing animals and unexpected plant roots are under investigation.

Below the biotic layer lies the hydraulic barrier. This layer must have a sufficiently low permeability to minimize percolation. It should also be placed below the maximum depth of frost penetration as well as evaporative depth.

Below the hydraulic barrier, a layer of foundation buffer with a layer of filter can be placed to protect the hydraulic barrier from being damaged by the underlying wastes. This layer also provides a stable working surface from which to construct the rest of the cover system.

3.0 DESIGN PHILOSOPHY

Current legislations require that wastes should be disposed of in an environmentally acceptable manner. One of the key issues in ensuring acceptable disposal is to reduce the production of leachate. Covers are therefore primarily designed to reduce infiltration of the surface runoff into the waste and hence reduce leachate production. In addition, covers should also be designed for long-term performance. It should be designed with sufficient resistance to the effects of erosion by water and wind, instability against slope failure and cracking, freezing and thawing, and degradation by plants and animals.

Leachate generation is generally equal to the amount of infiltration which percolates through the cover material. The method of estimating infiltration is usually based on the water budget approach which is commonly used in hydrological design. The amount of infiltration is equal to the total precipitation less the runoff, evapotranspiration and lateral flow in the internal drainage layer plus the change of moisture content in the soil. A schematic presentation of moisture flow in a cover system is shown in figure 2. This can also be summarized as:

$$\begin{aligned}\text{Infiltration} = {} & \text{Precipitation} - \text{Runoff} - \text{Evapotranspiration} \\ & - \text{Lateral flow in the drainage layer} \\ & \pm \text{Change in soil moisture storage}\end{aligned}$$

The amount of precipitation can be estimated from historical meteorological records and the help of some empirical formulas. While precipitation can occur in many forms, only rain and snow are considered in general.

The amount of runoff mainly depends on the gradient of the slope, the imperviousness of the cover, the size of the watershed and the conditions of the surrounding drainage system within the same watershed. A steeper slope and a more impermeable barrier can increase runoff and hence reduce infiltration. However, a steep slope is also more susceptible to slope erosion, which is one of the main considerations in design. Infiltration can further be reduced by

providing an internal drainage layer above the hydraulic barrier and by providing intercepting channels around the site. However, this will increase the cost of construction. Therefore, the design of a cover system is the balance of design objectives, the cost of construction and the availability of materials.

An approach called the rational method is expressed below and is often used to estimate runoff directly from precipitation data if reliable runoff coefficients are available.

$$Q = C.I.A.$$

where

Q = runoff volume

C = runoff coefficient

I = average precipitation intensity

A = the watershed area

Another approach which is known as the SCS (Soil Conservation Service) curve number method is also common in estimating runoff for a small watershed. This method is based on the following empirical expression.

$$Q = \frac{[P-(0.2)(S)]2}{P + (0.8)(S)}$$

where

Q = runoff for the time period considered

P = precipitation for the time period considered

S = the potential retention

The curve number CN is related to the potential retention S by the following formula

$$CN = 1000 / (S + 10)$$

The use of CN is just to make the plotting of the curve easier and has no physical meaning.

Evapotranspiration accounts for the major portion of the soil moisture lost from a typical vegetative cover system. The amount of evapotranspiration is usually estimated by a number of empirical formulas which are available in most hydrological test books.

The Environmental Protection Agency (1985)/1/ in the U.S. has developed a computer program, HELP (Hydrologic Evaluation of Landfill Performance), which is maintained by the U.S. EPA Hazardous Waste Engineering Research Laboratory. HELP allows a designer to input specific climatologic data of a site as well as the thickness and hydraulic characteristics of an individual layer in a cover system for parametric studies in order to come up with an optimum design.

The model is based on the hydrologic process and the flow of water in porous materials. Run-off is computed using the Soil Conservative Service Runoff Curve Number method. Percolation and vertical water flow are modeled using Darcy's law for saturated flow with modifications for unsaturated conditions. Lateral drainage is computed analytically from a linearized Boussinesq equation corrected for non-linear cases. Evapotranspiration is estimated by a modified Penman method adjusted for limiting soil moisture conditions.

Climatologic data to be input into the program include daily precipitation, mean monthly temperature, mean monthly solar radiation, leaf area index and winter cover factors. Leaf area index is defined as the ratio of the leaf area of actively transpiring vegetation to the nominal surface area of land on which the vegetation is growing. Winter cover factor, varying from 0 to 1.8, accounts for the evapotranspiration of plants in the growing season.

Vegetative cover data are also a part of the input to take into account the effect of the vegetation. The user must specify an evaporative (root) depth. Seven default values are available which represent bare ground (no vegetation), excellent, good, fair and poor stands of grass, and good and fair stands of row crops. Depending upon the default vegetation type selected, the hydraulic conductivity of the soil within the evaporative zone is corrected for

the effects of the roots. The leaf area factor discussed above is also modified depending on the type of vegetation.

Input soil data must be provided by the user. The hydraulic characteristics and the size, thickness and the slope of each layer are entered manually.

4.0 COVER MATERIALS

A cover system is usually made up of one or more of these three types of materials: natural soils, stabilized soils and synthetic membranes or man-made materials. Covers can consume relatively large amounts of construction materials. Owing to the availability and the relatively low cost of construction, natural soils are usually the predominant material of choice. However, not any type of soil can be used indiscriminately as a cover material. For instance, gravels and coarse sand are good drainage materials but are unsuitable to form an impervious blanket. If a suitable soil is not available within an economic haul distance from a site, synthetic membranes and man-made materials or stabilized soils using enhancement additives can also be considered.

Natural Soils

Presented in Table 1 is the classification of soil into groups with respect to its engineering properties. This classification is widely used in engineering design. The engineering properties that are important in the design of a cover system are particle size distribution, density, moisture content, permeability, strength and consolidation properties. Presented in Table 2 are the average properties of soils with respect to the grouping. Presented in Table 3 is the relative ranking of the soil groups with regard to cover-related engineering behaviour.

Stabilized Soils

The properties of natural soils can be improved by mixing with property enhancement additives. Common types of additives that can reduce the permeability are bentonite, cement, lime, fly ash and bituminous material.

Bentonite is commonly used in the construction of a soil liner because of the low permeability and the sorption property. Bentonite is a natural material rich in montmorillonite, a clay mineral which is extremely fine, and has high water absorbency and swelling characteristics. These properties make it very impermeable and allow it to close up cracks. However, bentonite is susceptible to piping and its hydraulic properties are highly dependent upon the chemical conditions of the ground water. In addition, if bentonite is applied on site, the application rate and the mixing must be carefully controlled, otherwise, inadequate mixing can result in an area of localized higher permeability.

Mixing soil with cement can result in relatively low permeability. However, the brittleness of the end product and the high cost of cement may sometimes render this option impractical. The soil-cement mixture should be designed on the basis of a laboratory testing program. Table 4 gives some examples of the permeability of cement treated soils. It is noted that the degree of compaction is also as important as the cement content in determining the permeability.

Lime, fly ash, and cement are often mixed with soil to form an impervious blanket. The design procedure is usually a trial-and-error approach. The disadvantage of these additives is that a relative rigid layer is formed, which is susceptible to cracking and differential settlement unless a stable foundation is provided.

Generally, bituminous materials are suitable in reducing the permeability of coarse-grained soils. Bituminous materials are generally more flexible than cement but are still vulnerable to a high degree of differential settlement.

Synthetic Materials

If a large volume of suitable soil is not available within economical haul distance around the site, synthetic materials can be used. Some common types of synthetic materials that have been used as covers are:

- Concrete
- Asphalt
- Geomembranes
    - plastic
    - rubber
    - combinations of plastic and rubber
- Geotextiles
- Industrial waste
    - fly ash
    - residual

Concrete has been used in the past to line hydraulic structures. Problems with cracking, leakage at construction joints, costs of labour and materials and the advent of cheaper and more flexible competitives have limited its use as a hydraulic barrier.

Asphalt can be used as a hydraulic barrier in the form of a hot sprayed asphalt membrane, asphalt emulsions, a sprayed asphalt membrane with reinforcement, asphalt concrete and a prefabricated asphalt lining. An asphaltic hydraulic barrier is more flexible than concrete but is still vulnerable to cracking under high differential settlement. The characteristics of the asphalt might also be affected by the chemicals in the landfill.

Geomembranes have been used extensively in the field of hazardous waste disposal. Common types of geomembrane used as a liner in a waste disposal site are given in Table 5. The advantages of using geomembranes are that they are manufactured in a factory where quality

control is more reliable and that they are more flexible. The disadvantages include the fact that the chemical resistance of the membrane must be determined for each job as well as leakage at the joints and the unknown effects under the long-term exposure to a biotic and/or mechanically hazardous environment.

Fly ash possesses pozzolanic properties and can be mixed with lime or cement to form a stable, low-permeability material. Recent research indicates that fly ash can also be used to support plant growth. The use of fly ash as a cover material is discussed more fully in Section 5.

Organic residual such as paper-mill slimes are fine in size and may be used to support plant growth. The use of mine and metallurgical residuals as cover material have been under investigation. Weathered blasted furnace slag had been used successfully as a temporary erosion control at the Nanticoke TGS fly ash lagoon.

5.0 FLY ASH AS A COVER MATERIAL

A large quantity of fly ash is produced from the combustion of pulverized coal in electric generating stations. Although fly ash has been proven to be a valuable pozzolanic material in concrete technology and a useful material for roadbase construction and other utilization options, only about 25% of the material has been utilized currently. The rest of the ash is usually disposed of by the landfilling method. Current studies have shown that fly ash can be used as a cover material./2/

Fly ash is composed predominately of silt size particles. Experiments showed that untreated fly ash compacted at an optimum water content can have a permeability of about 10^{-5} cm/sec. The permeability can be further reduced by 1 or 2 orders of magnitude with the addition of lime, cement, or bentonite. The low permeability of compacted modified fly ash makes it desirable to be used as a hydraulic barrier in a cover system.

Compacted, stabilized fly ash can resist frost action provided that the stabilized fly ash has a minimum compressive strength of 2800 kPa at 7-day. In general, this strength can be achieved with a cement content around 5%.

The strength of fly ash mixed with lime or cement can increase with time. This can allow a fly ash cover to be more erosion resistant than a soil cover.

6.0 FAILURE MECHANISMS REVEALED IN CASE HISTORIES

Golder (1985)/3/ has reviewed a number of case histories on the performance of cover systems. The failure mechanisms reported can be typically classified into two types. One type results in an increase of infiltration and the other type results in the erosion of the cover system.

The failure mechanisms that result in an increase of infiltration are:

- Inadequate final grade slope resulting in ponding.
- Insufficient compaction of the fill causing differential settlement, and subsequent ponding.
- Cracking due to dryness.
- Clogging of drainage system.
- Leakage in synthetic cover materials, usually along the joints.
- Inadequate application of bentonite (mix on site) resulting in a permeability larger than that desired.
- Penetration by burrowing animals or plant roots.

The failure mechanisms that can result in the erosion of the cover system or the collapse of the slope are listed below.

- Excessive grade causing slope instability.

- Inadequate surface drainage causing erosion of cover.
- Inadequate frictional resistance along the soil/synthetic membrane interface causing block slippage.

All these failure mechanisms must be carefully considered in the design stage.

7.0 CONSTRUCTION PRECAUTIONS

The hydraulic barrier is the most important element in a cover system. It should be carefully protected from being damaged during construction.

Construction equipment running over the cover system should be carefully monitored and controlled. One of the most common failure mechanisms of a cover system is the tearing and cracking of the material due to impact from construction equipment. Sufficient thickness of the protective layer must be placed to prevent puncture and tearing of the material during compaction and operation above the cover system.

Because it is impractical to construct a cover system across an entire site before beginning the next one, the construction of each layer must be sequenced so that the leading edge of the lower layer is ahead of the upper layer.

During construction, ponding should be avoided by providing drainage to surface runoff at all time and by constructing the surface at a uniform grade. It is recommended to proceed the construction in an uphill fashion. In this manner, surface runoff will be drained away from the site.

Traffic patterns of the construction equipment on the final soil layer should be running across the slope to minimize the initiation of rills.

Care must be taken during construction to prevent accidental mixing of materials from one layer into another layer. This is most likely to occur as a result of heavy rainfall during construction. If heavy rainfall does occur, the affected area near the working face should be cleaned up before construction proceeds.

If clay is used as a barrier material, it should be compacted soon after placement to make it more erosion resistant. A compacted clay surface should be scarified or roughed before the next lift is placed upon it. If heavy rainfall is anticipated, the clayey working face may be covered with plastic sheeting, or with geotextile to reduce the erosive power of raindrops.

Sharp edges should be avoided below or above the hydraulic barrier because this will puncture the barrier. Each layer of soil placed should be compacted at no thicker than 150 mm.

Materials that are susceptible to frost penetration should be placed below the frost line.

When additives are introduced to stabilize the soil or other materials, mixing can be either done in place or in a mixing plant. The latter provides better quality products. Mixing in place can also produce acceptable results provided that there is regular monitoring and proper control of the mixing.

Geomembranes are susceptible to failure due to the strain caused by folding and temperature changes and due to tension caused by wind and anchorage. Folding can cause intensive local stress and may crack the geomembrane and it should be avoided. Some geomembranes exhibit a high degree of expansion and contraction when exposed to variations in temperature. This will cause additional stress at the seam. Therefore it is necessary to make sure that seams are properly formed and that the type of geomembranes used can withstand such changes due to temperature variations. In large open areas, wind force can be considerate. If the end of the membrane is left unanchorage, damage could result from the flapping of the membrane caused by wind. This problem can be overcome by anchoring the edges.

8.0 TESTING AND CONTROLS

Good quality control in the construction stage is very important in ensuring a cover to perform as desired. The scale of the control depends on the size of the project and also on the sensitivity of the surrounding environment when subject to contamination.

The quality control of the construction of a cover system depends mainly on field testing and is usually supplemented by laboratory tests that simulate the field conditions. The testing evaluates the criteria that have been used in the design stage and ensures that such criteria are met during construction. The criteria that are important to cover design are the degree of compaction, the permeability of the different type of layers, the degree of mixing if the materials are mixed on site, the imperviousness of the membrane joints, and last but not least, the chemical compatibility of the cover with the waste leachate.

The degree of compaction can be determined by measuring the density and the moisture content of the soil on site. The degree of permeability can be measured either globally or locally. Global permeability can be determined by a large-scale pumping test whereas local permeability can be determined by constant or falling head permeability tests on a local spot. For measuring a very small permeability, a tensiometer can be used which measures suction in soil. If the soil is mixed with an additive such as bentonite on site, the degree of mixing can be determined quite accurately by determining the particle size distribution of the mix.

The successful application of synthetic membranes demands on a very tight quality control and qualified installation to ensure that the synthetic material is not damaged. The membrane joints should be carefully inspected on site and laboratory tearing tests should be conducted to verify the strength of the joints.

The interaction between the cover and the wastes should also be investigated so that the leachate will impose no undesirable short-term or long-term effects on the cover.

9.0 MONITORING AND INSTRUMENTATION

Monitoring serves not only to provide information on the performance of the cover, but also provide warning signals to the authorities should there be any excessive leakage of hazardous elements to the environment. An effective monitoring program must be designed based on a thorough understanding of the site and the waste characteristics, monitoring and analytical techniques, and the sensitivity of the environment subject to contamination.

Monitoring techniques generally consist of the observation of water level and water quality in the vicinity of the landfill site, usually by means of conventional monitoring wells. However, there are some other techniques that can also provide a simple and cost-effective means of monitoring the performance of a cover system.

Physical inspection on a regular basis can easily identify if cracks, pondings or settlements are developed on the cover. These problems should be rectified before they become evident.

Measuring pore-water pressure in the impervious layer of a cover system can also provide a good indication of the amount of water that might have passed through the cover. Pore-water pressure can be measured by piezometers. In case of unsaturated soil where negative pore water pressures exist, tensiometers can be used.

Drainage layers can be provided at the bottom of a solid waste landfill site so that the leachate, if any, can be collected for analysis. If the leachate is found to be hazardous to the environment, it should be properly treated before being released to the ground water system. The results of the analysis can also provide invaluable records for the design of future landfill sites.

The amount of infiltration can be measured by installing lysimeters just below the cover. Hims, Lee and Gillham (1984)/4/ describe the measurement of infiltration through landfill covers with lysimeters.

Settlement markers can also be installed on site so that accurate measurements can be recorded regularly.

10.0 MAINTENANCE

The life span and the performance of a cover can be well kept by providing good maintenance to the system. Sometimes, simple maintenance work that can be carried out at relatively low cost is very effective in keeping a cover in good shape. Such work includes mowing of vegetation, filling of a depression due to settlement, clearing clogged drainage, repairing leaks along seams or cracks on synthetic membranes, removal of burrowing animals and replacing eroded vegetation.

11.0 SUMMARY

A cover is a very important structure that can minimize the production of leachate within the waste material and can also keep the position of the water table low, so that the landfill mound is stable. A cover must be properly designed, built with appropriate materials, well-constructed, and effectively maintained. The design must consider the hydrological and the hydrological conditions of the site, the availability of suitable materials in the proximity of the site, and the sensitivity of the environment when subjected to contamination. The cover chosen must be able to minimize infiltration and resist erosion. A system of quality control must be developed to ensure the quality of the construction. Post construction monitoring and a maintenance program must also be developed to ensure the long-term performance of the cover system.

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Approved by:

T.J. Carmichael

for T.W. Klym
Manager
Civil Research Department

Prepared by:

H.T. Chan

H.T. Chan
Senior Engineer
Soil Sciences Section

Reviewed by:

T.J. Carmichael

T.J. Carmichael
Supervising Engineer
Soil Sciences Section

HTC:cm

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TABLE 1

Typical Correspondence Between USCS and USDA Soil Designations

(A) USDA Textural Types Corresponding to USCS Soil Designations

USCS Soil Type	USDA Soil Types
GW	Same as GP (except well graded in grain sizes)
GP	Gravel, very gravelly sand (less than 5% silt and clay)
GM	Very gravelly sandy loam, very gravelly loamy sand, very gravelly silt loam, very gravelly loam
GC	Very gravelly clay loam, very gravelly sandy clay loam, very gravelly silty clay loam, very gravelly silty clay, very gravelly clay
SW	Same as SP (except well graded in grain sizes)
SP	Sand, gravelly sand (less than 20% very fine sand)
SM	Loamy sand, sandy loam; sand; gravelly loamy sand and gravelly sandy loam
SC	Sandy clay loam, sandy clay; gravelly sandy clay loam and gravelly sandy clay
ML	Silt, silt loam, loam, sandy loam
CL	Silty clay loam, clay loam, sandy clay
OL	Mucky silt loam, mucky loam, mucky silty clay loam, mucky clay loam
MH	Silt, silt loam (highly elastic, micaceous or diatomaceous)
CH	Silty clay, clay
OH	Mucky silty clay
PT	Muck, peat

(B) USCS Soil Types Corresponding To USDA Soil Terminology

USDA Soil Type	USCS Soil Type
Gravel, very gravelly loamy sand	GP, GW, GM
Sand	SP, SW
Loamy gravel, very gravelly sandy loam, very gravelly loam	GM
Loamy sand, gravelly loamy sand, sand	SM
Gravelly loam, gravelly sandy clay loam	GM, GC
Sandy loam, gravelly sandy loam	SM
Silt loam, sandy clay loam (with fine-grained sand)	ML
Loam, sandy clay loam	ML, SC
Silty clay loam, clay loam	CL
Sandy clay, gravelly clay loam, gravelly clay	SC, GC
Very gravelly clay loam, very gravelly sandy clay loam, very gravelly silty clay loam, very gravelly silty clay	GC
Muck, peat	PT

TABLE 2

Average Properties of Soils

Soil Classification Group	Maximum Dry Density in Pounds Per Cubic Foot	Optimum Water Content, Percent	Void Ratio, C_e	Permeability k, Feet Per Year	@ 20 psi Percent	@ 50 psi Percent	C_e psi	C_{sat} psi	tan ϕ
GW	>119	<13.3	(*)	27,000 ± 13,000	<1.4	(*)	(*)	(*)	>0.79
GP	>110	<12.4	(*)	64,000 ± 34,000	<0.8	(*)	(*)	(*)	>0.74
GM	>114	<14.5	(*)	>0.3	<1.2	<3.0	(*)	(*)	>0.67
GC	>115	<14.7	(*)	>0.3	<1.2	<2.4	(*)	(*)	>0.60
SW	119 ± 5	13.3 ± 2.5	0.37 ± *	(*)	1.4 ± *	(*)	5.7 ± 0.6	(*)	0.79 ± 0.02
SP	110 ± 2	12.4 ± 1.0	0.50 ± 0.03	<15.0	0.8 ± 0.3	(*)	3.3 ± 0.9	(*)	0.74 ± 0.02
SM	114 ± 1	14.5 ± 0.4	0.48 ± 0.02	7.5 ± 4.8	1.2 ± 0.1	3.0 ± 0.4	7.4 ± 0.9	2.9 ± 1.0	0.67 ± 0.02
SM-SC	119 ± 1	12.8 ± 0.5	0.41 ± 0.02	0.8 ± 0.6	1.4 ± 0.3	2.9 ± 1.0	7.3 ± 3.1	2.1 ± 0.8	0.66 ± 0.07
SC	115 ± 1	14.7 ± 0.4	0.48 ± 0.01	0.3 ± 0.2	1.2 ± 0.2	2.4 ± 0.5	10.9 ± 2.2	1.6 ± 0.9	0.60 ± 0.07
ML	103 ± 1	19.2 ± 0.7	0.63 ± 0.02	0.59 ± 0.23	1.5 ± 0.2	2.6 ± 0.3	9.7 ± 1.5	1.3 ± *	0.62 ± 0.04
ML-CL	109 ± 2	16.8 ± 0.7	0.54 ± 0.03	0.13 ± 0.07	1.0 ± 0.2	2.2 ± 0.0	9.2 ± 2.4	3.2 ± *	0.62 ± 0.06
CL	108 ± 1	17.3 ± 0.3	0.56 ± 0.01	0.08 ± 0.03	1.4 ± 0.2	2.6 ± 0.4	12.6 ± 1.5	1.9 ± 0.3	0.54 ± 0.04
OL	(*)	(*)	(*)	(*)	(*)	(*)	(*)	(*)	(*)
MH	82 ± 4	36.3 ± 3.2	1.15 ± 0.12	0.16 ± 0.10	2.0 ± 1.2	3.8 ± 0.8	10.5 ± 4.3	2.9 ± 1.3	0.47 ± 0.05
CH	94 ± 2	25.5 ± 1.2	0.80 ± 0.04	0.05 ± 0.05	−2.6 ± 1.3	3.9 ± 1.5	14.9 ± 4.9	1.6 ± 0.86	0.35 ± 0.09
OH	(*)	(*)	(*)	(*)	(*)	(*)	(*)	(*)	(*)

[1] Based on USBR experience;
The ± entry indicates 90% confidence limits of the average value

*Denotes insufficient data
NOTE: 1 ft/yr equals approximately 10^{-6} cm/sec (precisely, 9.665×10^{-7} cm/sec)

TABLE 3

Ranking of USCS Soil Groups with Regard to Cover-Related Engineering Behavior

Best group appears first, worst group appears last; groups separated by commas have equal rank.

Trafficability, GO/NO-GO:	GW, GP, SW, SP; SM, GH, SC, GC, CH; CL, MH; ML, OL, OH, Pt
Trafficability, Stickiness:	GW, GP, SW, SP, GM, SM, ML, OL, CC, SC; CL; MH; CH
Trafficability, Slipperiness:	GW, GP, SW, SP; GM; SM; GC, SC, ML, OL; CL; MH; CH
Impede Water Percolation:	CH; CL; MH; ML, GC, SC, GM; SM; SW; GW; SP; GP
Assist Water Percolation:	GP, SP; GW; SW, SM, GM; SC; GC; ML, MH; CL; CH
Impede Gas Migration:	CH, CL, ML,L GC, SC, SM; SP, GM, SW, GP; GW
Assist Gas Migration:	GW, GP, SW; GM, SP; SM; SC; GC, ML; CL; CH
Fire Resistance:	CH; CL, ML; GC, SC, SM, SP, GM; SW: GP; GW
Water-erosion Resistance:	GW, GP; SW, SP; GC, GM; Pt, SM; SC, OH; CH; MH; OL, CL; ML
Wind-erosion Resistance:	GW, GP, SW, SP, GM; SM, GC; SC, ML, OL; CL; MH; CH
Dust Control:	GW, GP; SW, SP; GM; SM; GC; SC; ML, OL; CL; MH; CH
Crack Resistance:	GW, GP, SW, SP; SM; GM; SC; GC, ML; OL; CL; OH, MH; CH
Reduce Freeze Action: Fast Freeze:	CH; CL; ML; GC, SC; SM; GM, SP; SW; GP; GW
Reduce Freeze Action: Saturation:	GW, GP; SW, SP; CH; CM; SM; SC, GC; CL, OL; MH; ML
Side Slope—Seepage:	CH; CL; MH; ML; GC; SC; GM; SM; SW; GW; SP; GP
Side Slope—Drainage:	GP; SP; GW; SW; SM; GM; SC; GC; ML; MH; CL; CH
Discourage Burrowing:	GW, GP; SW, SP; GM; SM; GC, SC; ML, OL; CL; MH; CH
Impede Vector Emergence:	CH; MH; CL; SC; GC; ML, OL; SM; GM; SP, SW; GP, GW
Support Vegetation:	SC; SM; Pt, ML; MH, OL; CC; GM; CL; CH, OH; SP, SW; GP, GW
Future Use, Natural:	SC; SM; Pt, ML; MH, OL; GC; GM; OL; CH, OH; SP, SW; GP, GW
Future Use, Foundation:	GW, GP, SW, SP; SM; GM; SC, GC, CH; CL; MH, ML; OL; OH; PT
Side Slope Stability	"determine on basis on laboratory testing"
Discourage Birds:	"all soils are suitable"

TABLE 4

PERMEABILITY OF CEMENT-TREATED SOILS

Soil Number or Sample Identification	Dry Density, pcf	Moisture Content, Percent	Cement Content Percent by Volume	Type of Soil-cement	E, Coefficient of Permeability, ft per year	USDA Texture	Gradation Analysis, Percent Passing							AASHTO Soil Class[a]	Cement Requirement by Volume[b]
							3/4	4	10	40	200	.05	.005		
Standard Ottawa sand	108.2	10.8	0	Compacted	48,750	Coarse sand	(100% pass #20; 0% pass # 30)							A-1-b(0)	--
	112.8	9.4	5.7	Compacted	6,940										
	117.6	9.7	11.3	Compacted	76										
SP sand, U H-26 Idaho	--	--	0	Plastic	2,460	Sand	100	99	98	73	9	8	3	A-3(0)	--
	98.6	24.1	8	Plastic	130										
	99.8	20.1	8	Plastic	130										
	100.3	18.8	20	Plastic	0.8										
Graded Ottawa sand	101.2	13.7	0	Compacted	16,700	Sand	100	100	100	#50	#100	--	--	A-1-a(0)	--
	104.7	13.6	5.3	Compacted	473					28	2				
	107.4	12.1	10.3	Compacted	21.4										
PCA soil No. 7018 Florida	101.0	12.2	0	Compacted	746	Sand	100	100	100	91	7	1	--	A-3(0)	10.0
	100.9	13.3	5.1	Compacted	562										
	103.6	12.3	6.3	Compacted	192										
	105.3	12.0	9.2	Compacted	21.1										
PCA soil No. S-2 Illinois	100.8	14.9	0	Compacted	4,960	Fine sand	100	100	100	96	13	12	2	A-2-4(0)	8.0
	99.9	14.7	5.1	Compacted	1,359										
	104.0	15.1	6.3	Compacted	59.5										
	104.8	15.1	9.2	Compacted	11.5										
PCA soil No. 6998 Maine	104.8	10.6	0	Compacted	2,400	Coarse sand	100	100	96	51	5	2	--	A-3(0)	7.0
	107.2	9.5	5.3	Compacted	651										
	111.7	10.3	6.8	Compacted	36.2										
	113.4	10.2	9.9	Compacted	7.6										
PCA soil No. 6863-2 Maryland	106.9	10.3	0	Compacted	1,640	Sand	100	100	100	77	4	--	--	A-3(0)	8.5
	106.6	10.8	5.3	Compacted	90.3										
	112.4	10.3	6.8	Compacted	25.6										
	114.4	10.3	10	Compacted	3.6										
SP sand, U H-165 Utah	100.1	16.0	0	Compacted	356	Fine sand	100	99	99	96	6	6	1	A-3(0)	--
	105.8	14.8	6	Compacted	19.8										
	109.3	13.5	12	Compacted	1.1										
PCA soil No. 7019 Florida	101.0	13.8	0	Compacted	144	Fine sand	100	100	100	96	2	--	--	A-3(0)	11.0
	106.7	13.3	5.1	Compacted	33										
	108.2	13.4	6.5	Compacted	0.3										
	108.8	13.4	9.5	Compacted	0.02										

[a] All soils nonplastic.
[b] Cement requirement based on ASTM Standard Freeze Thaw and Wet-Dry Tests for Soil-Cement Mixtures and PCA Paving Criteria.

Source: Portland Cement Association's Soil-Cement Information Bulletin IS173.02P

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TABLE 5

Major Types of Geomembranes Used as Liners
(Koerner, Martin and Lord 1986)/5/

- Plastic
  - Polyvinylchloride (PVC)
  - Polyethylene (low, medium and high density)
  - Chlorinated polyethylene (CPE)
  - Elasticized Polyolefin
  - Polyamide (PA)
- Rubber
  - Isoprene - Isobutylene (butyl)
  - Epichlorohydrin rubber
  - Ethylene propylene diene monomer (EPDM)
  - Polychloroprene (neoprene)
  - Ethylene propylene (EPT)
  - Ethylene vinylacetate (EVA)
- Combinations
  - PVC - nitrile rubber
  - PE - EPDM
  - PVC - ethyl vinyl acetate
  - crosslinked CPE
  - Chlorosulfonated polyethylene (CSPE)

Surface (Vegetative Support)

Filter(s)

Biotic Barrier

Drainage

Hydraulic Barrier

Foundation (Buffer)

Filter(s)

Gas Control

Waste

FIGURE 1

STRUCTURE OF A COVER SYSTEM

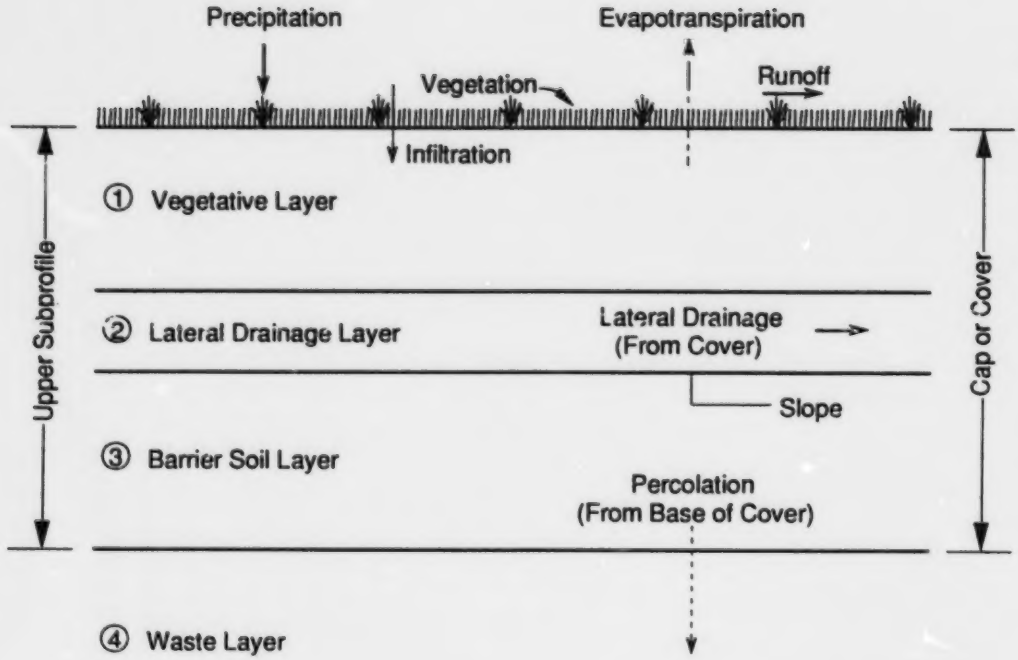

FIGURE 2

SCHEMATIC THREE-LAYER COVER SYSTEM